A CASE EXAMPLE OF UTILIZATION OF CONCRETE PAVEMENTS APPLYING A 3DMC SYSTEM
- UTILIZATION OF AN IT-BASED CONSTRUCTION TECHNIQUE TO SLIPFORM PAVING METHOD

Takashi SEKIGUCHI
Taisei Rotec Corporation
1456, Kamiya, Kounosu, Saitama 365-0027, Japan
takashi _sekiguchi @taiseirotec.co.jp

ABSTRACT

As for construction techniques applying Information Technology (IT) equipment in Japan, an IT-based construction system for forming structures as designed by utilizing the GNSS or auto-tracking total station not only for workmanship control of pavements, but also for control of construction machinery is being established in the field of paving work. As Japan is evolving towards an ageing society, with a lowering birthrate, this system is one of the effective means of assuring quality as required in light of the diminishing number of skilled machinery operators and construction site operatives, and can thus be expected to improve the efficiency of work execution. This paper reports on a concrete pavement we constructed by a slipform paving method utilizing a 3D machine control system based on auto-tracking total stations for the first time in Japan.

1. INTRODUCTION

IT-based construction is a technique of carrying out construction work with higher productivity, higher efficiency and higher accuracy by utilizing electronic information obtained through the use of Information Communication Technology (ICT), aiming at streamlining work management and execution procedures. In Japan, strategic measures for dissemination of IT-based construction are being pushed forward in academic, business and governmental circles. In the construction projects under the direct jurisdiction of the Ministry of Land, Infrastructure and Transport, IT-based construction is prescribed to be promoted as a standard construction method by 2010 for large-scale projects and by 2012 for medium-and small-scale projects [1)].

Among others, a Three Dimensional Machine Control (3DMC) system has been put to practical use, improved dramatically and disseminated rapidly in recent years in the pavement industry.

Typical examples of the recent 3DMC systems are (1) high-precision Global Navigation Satellite System (GNSS), an amalgam of GNSS and laser technology that enables control in the so-called "sub-centimeter" accuracy range, and (2) control systems utilizing an auto-tracking total station (typically considered as a construction surveying instrument).

As these systems execute work while positioning and measuring three-dimensional (3D) positional information (coordinates) in real time, the following advantages are generally known:

1) Work is performed according to planned 3D design data. Therefore, highly accurate operations can be done even by less experienced operators, contributing to skill-saving.
2) The existing conditions relative to the planned design height are easy to grasp, and conventional point-to-point control by use of finishing stakes can be replaced by continuous, real-time surface control. Therefore, productivity improvement is promising.
3) Management from machine control to data control after work can be centralized with reference to design data. Therefore, streamlining of work procedures is promising.
4) Removal of items such as wooden stakes, steel rods, guide wires and other surveying "setting out" equipment, typically employed to mark-out the work area, and provide control inputs to machinery, is considered advantageous to remove hazards to human workplace safety. This feature of 3DMC

5) systems furthermore removes restrictions in the movement of machinery and personnel around the jobsite and paving machinery, thus offering further potential to boost jobsite productivity.

At Taisei Rotec, we implemented the high-precision GNSS system and auto-tracking total station 3DMC system three years ago and have worked since then toward dissemination of paving techniques applicable to these systems.

2. COMPARISON OF HIGH-PRECISION GNSS SYSTEM AND AUTO-TRACKING TOTAL STATION 3DMC SYSTEM

Table 1 shows a comparison of the high-precision GNSS system and the auto-tracking total station 3DMC system

Table 1. Comparison of 3DMC systems

Item	High-precision GNSS system	Auto-tracking total station 3DMC system
Restriction on application	Upward visibility and weather conditions	Weather conditions
System configuration	Multiple machines can be controlled by one system.	One machine is controlled by one system.
Adaptive scale	Large-scale work in which multiple machines operate simultaneously in same paving section	Type of work is typically performed by single machine Medium- or small-scale work

Lately, we have constructed a continuous reinforced concrete slab pavement by applying the 3DMC system with auto-tracking total stations to the slipform paver for the first time in Japan. This paper presents the outline and configuration of the system and a case example of work execution.

3. SYSTEM CONFIGURATION FOR APPLICATION OF 3DMC SYSTEM TO SLIPFORM PAVING METHOD

3-1 Slipform paving method

The slipform paving method is a way of pouring a concrete slab or a concrete structure continuously without installing a mold by using a self-propelled paving machine that has the function of (1) supplying concrete, (2) spreading, (3) compacting, (4) forming and (5) surface finishing. In the country, conventional concrete slab pavements have been generally constructed by the setform paving method that uses a mold and carries out spreading, compacting, forming and surface finishing operations by using several paving machines. At present, however, the slipform paving method is now becoming standard for construction of concrete pavements.

An external view of the slipform paver is given in Photo 1.

Photo 1 External view of slipform paver

3-2 Concept of the 3DMC system applying an auto-tracking total station

The system concept for application of the auto-tracking total station 3DMC system to the slipform paving method is as follows:

1) A mast is installed on the left and right sides of the rigid machine frame of the slipform paver, and a 360-degree prism for collimation with total stations is attached to the top of each mast these two prisms are measured 5-10 times per second by two corresponding auto-tracking total stations.
2) The measured values are transmitted to a machine PC installed on the machine via wireless data modems.
3) Vertical and horizontal inclinations of the mold are also provided to the machine PC by dual-axis inclination sensors attached to the lower part of each mast.
4) The current position, height, inclination and moving direction (roll, pitch and heading) of the mold – the “six degrees of freedom” - are calculated by continuously using the information on the mold position, height and inclination.
5) The actual positional information (position, height and inclination) of the mold is instantaneously compared with the three-dimensional design model within the machine PC. Differences (deviations) of the actual values from the design values are transmitted as correction values to the machine controller (for hydraulic control) of the machine, and correction of the paving height, and vertical and horizontal inclinations as well as steering of the machine during work are all controlled automatically by means of hydraulic control.

Figure 1 illustrates the concept of the auto-tracking total station 3DMC system.

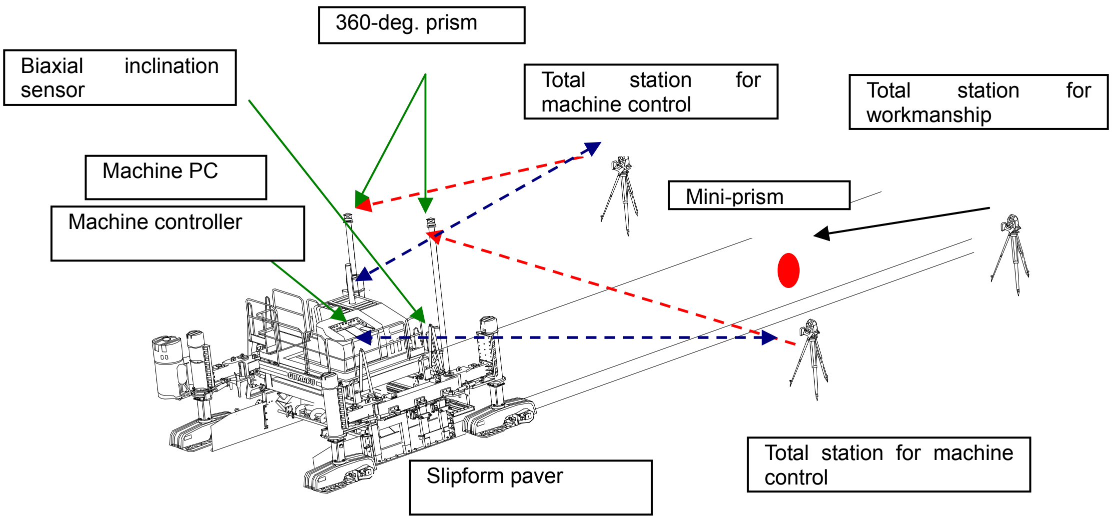


Figure 1. Concept of 3DMC system

3-3 Role of the control equipment of the 3DMC system with auto-tracking total stations

The control equipment of the 3DMC system with auto-tracking total stations is as follows:

(a) Total stations (three)
Two total stations for machine control perform automatic tracking, and one total station for workmanship measurement measures the leveling height and finished height (Photo 2). The geodetically-independent check provided by the third total station is considered essential for quality-assurance purposes.

(b) 360-degree prisms (for total stations)
Located at known reference points (three or more) when installing the total stations in any positions and used to measure and calculate the position coordinates of the total stations (Photo 3).

(c) Mini-prism for workmanship measurement (one)
Installed on the pavement surface immediately after leveling off or after completion of concrete

placing and used to measure the workmanship of the pavement (Photo 4).

(d) Machine computer (one)

The main computer responsible for overall control of this system. It has three wireless modems for two-way transmission of data from the total stations (Photo 5).

(e) Machine controller

This device is built in the slipform paver proper. It receives instructions (correction values) from the machine PC to hydraulically control the height and traveling direction of four tracks (crawlers), front, rear, left and right (Photo 5).

(f) Dual axis inclination sensors (two)

Measure the vertical and horizontal inclinations of the paving machine and links data to the machine PC (Photo 5).

(g) 360-degree prisms (two for machine collimation)

Set as targets for machine collimation at the tops of the masts installed on the left and right sides of the rigid machine frame (Photo 5).

Photo 2 Total station

Photo 3 360-deg. prism x 3 for total station

Photo 4 Mini-prism For workmanship measurement

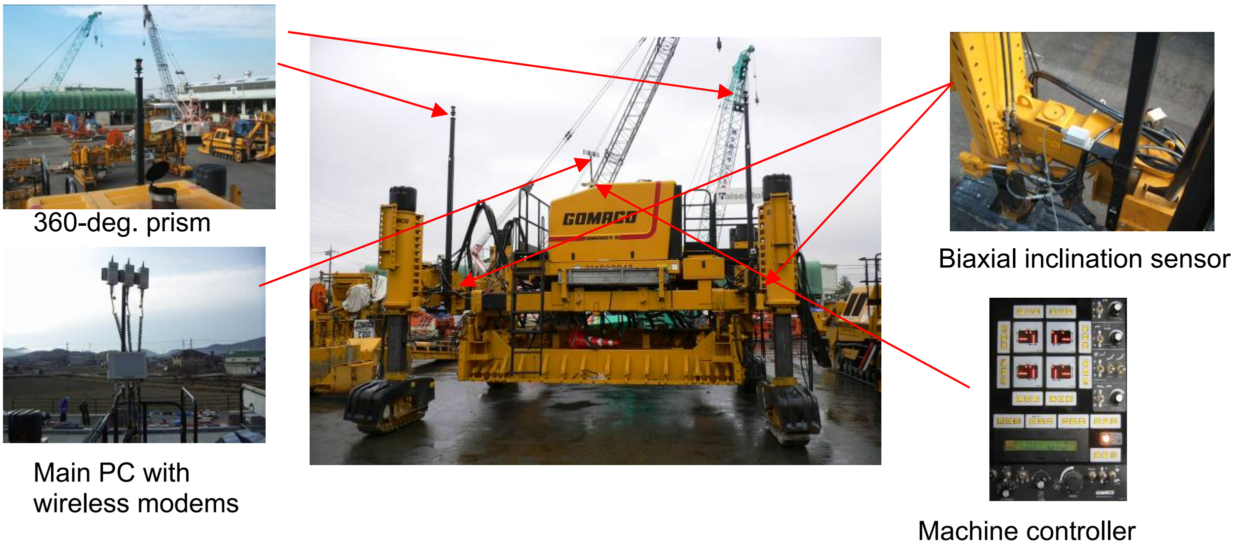


Photo 5 Slipform paver side control equipment

4. ADVANTAGES OF SLIPFORM PAVING METHOD APPLYING AUTO-TRACKING TOTAL STATION 3DMC SYSTEM

4-1 Comparison with the standard slipform paving method

In the conventional slipform paving method, fiducially objects such as finishing stakes serving as a reference for workmanship measurement, sensor lines for controlling the paving height and steering of the machine, etc. have had to be located at fixed intervals in the construction area by using surveying instruments. The paving machine operator has operated the machine to carry out site work, referring to these fiducially objects.

The slipform paving method applying the auto-tracking total station 3DMC system has the following advantages over the standard slipform paving method:

1) Getting rid of restraints by steering and height control, the paving machine operator can attend to high value-added work and quality control (workmanship control).
2) As the need for fiducially objects such as finishing stakes, sensor lines, etc. is eliminated, installation process steps are reduced and productivity improvement is promising. In addition, obstacles in the construction area are reduced, so paving work can be done smoothly and uniform quality is easily obtainable. Faults in handling leading to damage, slacking, etc. of sensor lines are eliminated, which also contributes to productivity improvement. Site safety is also improved, for reasons mentioned previously.
3) Inspection and measurement procedures are simplified and operations in proximity to the paving machine are reduced, so safety can be improved.
4) Different from the conventional paving method that performs control at points with reference to fiducially objects, the present paving method enables control at the surface according to design data along all points of the design. The effect of "sag" (catenary) between successive supporting "pins" of the conventional steel guidewire method is also eliminated completely, further aiding surface homogeneity. Moreover, steering and height control made in units of 3 mm in the standard slipform paving method become able to be done in millimeters in the auto-tracking total station 3DMC system. Therefore, paving work can be performed with higher accuracy.
5) A series of operation steps from machine control to workmanship control are performed with reference to design data, so data control can be centralized and execution management becomes able to be done efficiently.

4-2 Features of the applied 3DMC system

In the 3DMC system applying an auto-tracking total station, two types of machine control systems are available, i.e., ［1］ type that controls the paving machine directly by infrared laser emitted from the total station connected to the computer in which a control program is installed, and ［2］ type that controls the paving machine by comparing the positional information, measured by the total station and transmitted to the controller of the paving machine through the attached wireless modems, with the control data entered in the controller in advance. In the 3DMC system used on this site, the control system is of the type of ［1］. It is simplified in system configuration as compared with the system of the type of ［2］.

As for the configuration of the control system of the 3DMC system applying an auto-tracking total station in the country, a 3DMC system that combines one auto-tracking total station with slope sensors is being experimented with. In the slipform paving method, however, the paving machine is large-sized, so its deflections, etc. may affect the accuracy of work. In the present work, therefore, we adopted a system configuration that enables acquiring more accurate positional information on the paving machine by using two auto-tracking total stations and combines these stations with high-precision biaxial inclination sensors capable of measuring strains of the paving machine as well. As a result, the front, rear, left and right sides of the paving machine are made fully independently controllable, making it possible to perform work with higher accuracy.

5. INTRODUCTION OF A CASE EXAMPLE OF WORK EXECUTION

The work site was a new bypass road substituted for Route 180. The paving section was partly paved with concrete. On this site, a continuous reinforced concrete pavement was constructed by the slipform paving method applying the 3DMC system with auto-tracking total stations, aiming at improving quality and productivity.

An outline of the paving work is given in Table 2.

Table 2. Outline of the work

Name of work	Paving work in Ueki area of Soja Bypass
Work period	December 17, 2007 to January 30, 2008
Work site	Ueki area, Soja-city, Okayama Prefecture, Japan
Type of work	Continuous reinforced concrete pavement
Paving machine	Slipform paver
Paving width	4.215 m to 4.325 m
Paving length	382.5 m (4 lanes)
Quantity of work	6,500 m^2
Paving thickness	25 cm

A schematic flow of utilization of the auto-tracking total station 3DMC system in the present work is given in Figure 2.

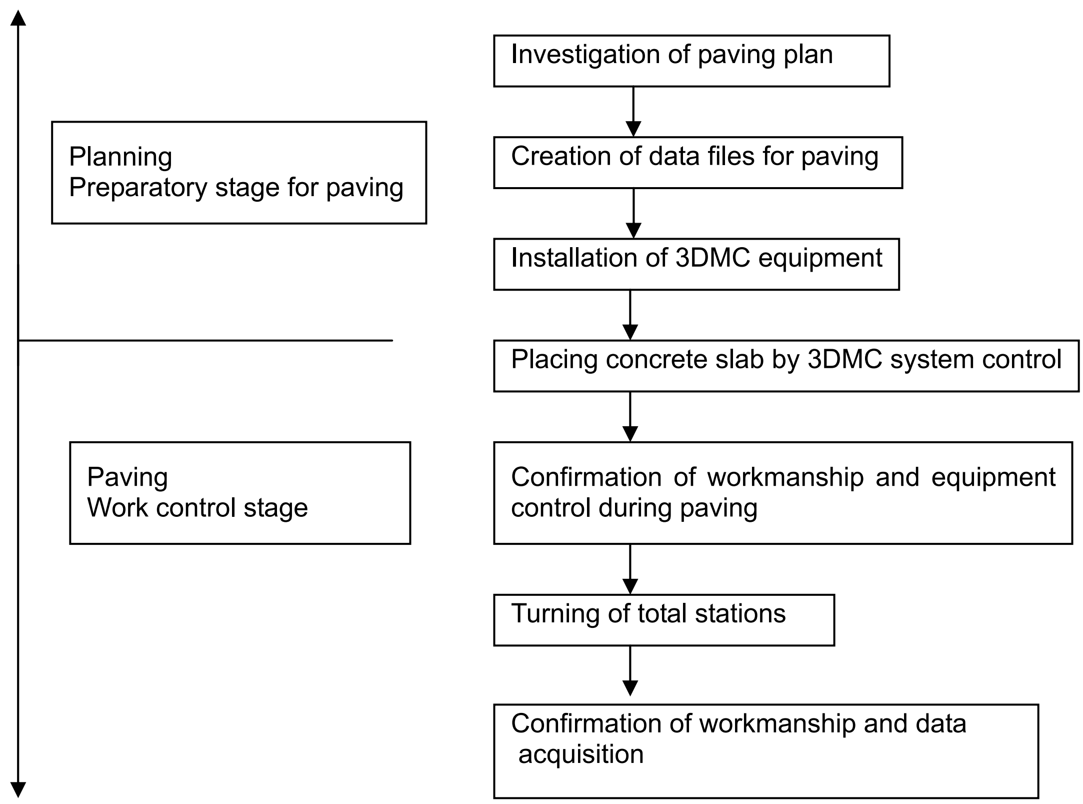


Figure 2. Schematic flow of utilization of auto-tracking total station 3DMC system

5-1 Preparation for paving

5-1-1 Creation of data file

[Design data file]

A design data file is necessary for system operation. Two methods are available for data creation:

1) Creating design data from three-dimensional CAD.
2) Creating and editing design data by Excel file.

Design data is either of the polyline data type consisting of horizontal alignment, longitudinal slope; cross slope and width or of the triangular mesh type that connects these lines with coordinates (X, Y and Z). In the 3DMC system applied in this case, most attention being focused on the construction of a road etc., the polyline type including elements of alignment was adopted. A data file of 500 points was created by the method of 2) in the present work.

Data on one cross section is defined as data of 50 points maximum and file data as data of 3,000 points maximum permissible. When the mold attached to the paving machine is outside the design data area, machine control at the total station becomes impossible, so design data needs to be created for an area slightly wider than the actual paving area, to allow for maneuvering of the machine during preparation prior to paving operation. With consideration to the movement of the paving machine, therefore, design data for lengths of 30 m before and behind relative to the paving length was also created. For the paving width, coordinates displaced outside by 1 m each from the actual paving width were made as design data. Further, for design data on a changing point of slope and a curve, data creation intervals had to be made shorter, to minimize the “chording” effect. On this site, the paving area was a straight section and the cross slope was uniform, so consideration was directed to the change in longitudinal slope. Thus, the design data locating interval was set at 5 m for the section of uniform longitudinal slope and at 1 m for the 10-m long sections before and behind the changing point of longitudinal slope.

[Reference point data file]

Reference point data serves as a reference for confirming the position coordinates of the total stations installed at the time of paving and needs to be located so as to surround the paving area.

In the present work, a reference point data file of 40 points was created in the same manner as the design data file.

With consideration to the installation efficiency of the total stations, reference points were located at 20-meter intervals so as to surround the paving area. As to the accuracy of reference points, the coordinates thereof were checked for accuracy by performing resurvey before the start of work. As a result of this check, each reference point was within an error of ±2 mm, so the coordinates were judged dependable. Being an important element for paving work, reference points should desirably be located securely so as not to displace easily. On this site, therefore, reference points were located on the concrete structure.

5-2 Installation of equipment

In order to carry out work by the slipform paving method applying the auto-tracking total station 3DMC system, it is necessary to install total stations and other system equipment. The precautions to be taken when installing the equipment are as follows:

1) Though not so dependent on the upward visibility as that of the GNSS, the system equipment should be installed in a position not affected by obstacles that interfere with the collimation with total stations (i.e. the “line of sight” to the prism), such as site vehicles, site personnel etc.
2) Investigate the collimation from before and behind relative to the paving direction, taking into account the paving conditions and paving length. On this site, the total stations were installed on the left side relative to the traveling direction of the machine where they were less subject to the influence of the material carrier truck and other vehicles.
3) Avoid areas where the ground is not good for installation as far as possible. Confirm the benchmarks at regular intervals to prevent possible displacement of tripods by subsidence or

vibration.

4) Install wireless modems for two-way transmission in the highest possible position and make the two-way transmission environment as good as possible.

5) Installing the prism masts of the machine proper higher makes them less subject to the influence of obstacles. However, the prisms become greater in amplitude with an increase in mast height. As a result, the prisms may become unable to be tracked by total stations. In the present work, the installation height of the prism mast was determined with consideration to the installation conditions of the total station, height of the material carrier truck, etc.

6) The maximum operation distance from the total station to the machine should be set at about 100 m as a target value, consistent with the experience of, and advice given, by the manufacturer of the 3DMC system.

5-3 Paving work

Ready-mixed concrete carried into the site by the material carrier truck is supplied to the machine proper through its belt conveyor. The supplied ready-mixed concrete is spread in the transverse direction by a screw auger and leveled off to the specified height by a mold. On this site, the concrete surface after formed was finished by an auto-float.

The state of work under way is shown in Photo 6.

Photo 6 State of work under way

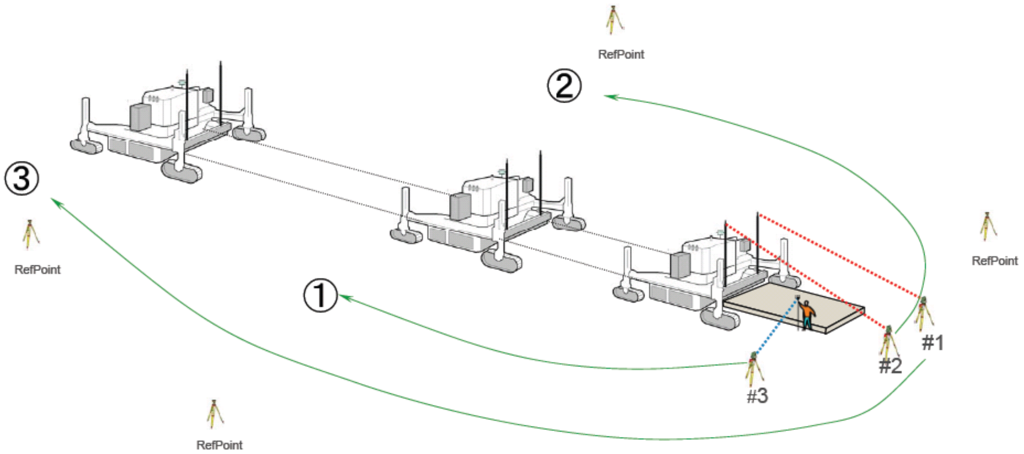
5-3-1 Adjustment during work and confirmation of workmanship

The leveling height is checked from time to time by the total station for workmanship measurement and mini-prism. Immediately after the start of work and in the neighborhood of the changing point of slope, it is necessary to well check the height at shorter measuring intervals. As to control in the vertical direction, the trackability of control depends greatly on the properties of ready-mixed concrete, so it is necessary to measure and check the pavement height at the proper time and make corrections or adjustments. On this site, in case that a structure such as circular waterway was already installed at the time of concrete placing, the height of the structure in the current state was measured. When the measured data was different from the design data, adjustments were made to the height of the design data. The state of measurement under way is shown in Photo 7.

Photo 7 State of workmanship measurement under way

5-3-2 Turning of total stations

By making three total stations move in rotation to the positions for machine control and workmanship measurement (movement setup), it becomes possible to carry out long-span work continuously. Figure 3 illustrates the basic concept of the turning of total stations. Errors in height of appliances during turning are corrected by the auto-correction function of the machine PC.



At start of work: Locate all total stations in rear collimation position.
Part 1: Move No. 3 total station to position for machine control.
Shift No. 2 total station to position for workmanship measurement.
Part 2: Move No. 2 total station to position for machine control.
Shift No. 1 total station to position for workmanship measurement.
Part 3: Move No. 31total station to position for machine control.
Shift No. 3 total station to position for workmanship measurement.

Figure 3. Basic concept of the turning of total stations (Nos.1, 2 and 3)

5-4 Results of application

The results of workmanship measurement are as follows:

1) Accuracy of position (accuracy relative to design line)
Accuracies of ±10 mm or better in the horizontal direction and ±6 mm or better in the vertical direction were acquired.

It should be noted that inaccuracies may be introduced and compounded by a number of potential sources – namely the total stations, inclinometers, 3DMC system, reference control points, range, atmospheric conditions (temperature, pressure, humidity), variations in concrete quality and consistency between deliveries, sub-surface quality (particularly iunder the tracks of the machine) and mechanical flexure of the machine.

2) Surface roughness of pavement surface
   Surface roughness σ was 1.0 mm or less (standard value: σ=1.8 mm or less).
3) By implementing this system, the following advantages over the standard slipform paving method were obtained:
   a) Preliminary jobs before work such as installation of control sensor ropes used in the standard slipform paving method, installation of finishing stakes for confirmation of workmanship were simplified. Therefore, the work period could be made 3 days shorter than originally planned, contributing to higher work efficiency.
   b) Obstacles such as sensor ropes, etc. were eliminated from around the paving machine and paving area. Therefore, the safety of work was improved. In addition, a wider passage zone for the material carrier truck could be obtained, so smooth supply of materials was ensured, contributing to higher work efficiency.
   c) A series of process steps from machine control to workmanship control were performed with reference to the site design data. Therefore, data control was centralized, contributing to streamlining work procedures.

5-5 Investigation from the aspect of work execution

When locating the machine at the work starting point, the mold position may be somewhat displaced relative to the work line due to measurement errors the total stations have. Therefore, it is necessary to correct the location by offsetting horizontal and vertical displacements. Further, the tracking response of control depends greatly on the properties of ready-mixed concrete, so it is necessary to measure and check the pavement height at the proper time and make corrections or adjustments.

In the present work, the paving speed was 1.0-1.5 m/min, averaging out at 1.2 m/min. The control frequency of the auto-tracking total station system used in the present work was 5-10 Hz. The control interval can be represented by equation (1):

$$W = 1000\, v/60\, f \quad \text{. . . . .} \quad (1)$$

where W: control interval (mm)
v: paving speed (m/min)
f: control frequency (Hz)

According to the calculation by equation (1), the machine was controlled here every 2-4 mm travels in the longitudinal direction. The relation between the paving speed and the control frequency is an element that affects the accuracy of position. As the slipform paver is very low in paving speed as compared with a leveling machine such as a motor grader, a sufficient accuracy of position can be acquired as seen from the execution results. In addition, the control frequency of the auto-tracking total station applied to the slipform paver can be presumed to be within a problem-free range.

6. SUMMARY

As a result of carrying out work by the slipform paving method applying the auto-tracking total station 3DMC system, the following information was obtained:

1) In cases where the coordinate system is reliable and the accuracy of survey is good as in the case of this site, it is possible to apply a method of creating design data and reference data files on the basis of a design drawing. When the workmanship does not completely conform to that planned on the drawing because the design is indefinite or the workmanship has changed from the original design or for other reasons, investigations need to be made on a method of creating design data by surveying the workmanship on the site by a total station.

2) Installation of equipment was good on this site. In the future, when constructing a curve, the collimation with total stations may become complex relative to the 360-degree prisms attached to the slipform paver. To avoid this complexity, making the left and right masts different in height can be considered as an effective measure.
3) In ordinary paving conditions without abrupt changes in slope etc. The control accuracy is about ±10 mm or better in the horizontal direction and about ±6 mm or better in the vertical direction. In the future, construction data will have to be accumulated to grasp the reliability of the system under different paving conditions.
4) When locating the machine at the work starting point, it is necessary to correct the location by offsetting horizontal and vertical displacements.
5) The trackability of control depends greatly on the properties of ready-mixed concrete, so it is necessary to measure and check the pavement height at the proper time and make corrections or adjustments.
6) The control frequency in slipform paving by the auto-tracking station 3DMC system is within a problem-free range of 5-10 Hz.
7) The efficiency and safety of work can be improved by adapting the auto-tracking station 3DMC system to the slipform paver, and work procedures can be streamlined by centralizing data control.

As seen from the foregoing, according to the measured data on the accuracy of position and surface roughness of the pavement, the slipform paving method applying the auto-tracking station 3DMC system gives results compliant to the prescribed standard values. Therefore, this system can be judged to be a paving system that fully meets the prescribed criteria for workmanship control.

7. CONCLUSION

In IT-based construction, preliminary jobs before work such as "processing of site design data," "on-site existing form survey," "positioning and survey of reference points," "comparison between design data and current state," etc. have an important influence on the accuracy and efficiency of work in actual construction. Processing of these jobs requires labors as well as specialized knowledge about machine characteristics, survey, IT equipment, etc. Implementation of IT-based construction offers a great advantage of labor-saving and skill-saving in work execution. On the other hand, it is necessary to contemplate the need for new technical capabilities, staff training, etc.

IT-based construction has the potential to become an effective tool for improving construction productivity and creating an attractive work site. For the future, we intend to apply the 3DMC system to various work sites and make further improvements while striving to encourage its dissemination.

REFERENCE

1) Conference for Promoting IT-based Construction: Strategy for Promoting IT-based Construction (July 2008)